

## Estimated corn yields using either weed cover or rated control after pre-emergence herbicides

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Because soil-residual PRE herbicides reduce and delay annual weed emergence and decrease later weed growth, susceptible weeds surviving or recovering from herbicide treatment reduce crop yields less than do untreated weeds. Recently, corn yields were shown to be reduced differently by untreated weeds emerging in and between crop rows. However, equations have not been reported before that relate corn yield to in-row and between-row weed cover of mixed weed populations recovering from PRE soil-residual herbicides. Published data from PRE herbicide screening research for 3 site-yr in Missouri were reanalyzed to characterize this relation. In-row and between-row weed cover of mixed weed populations, chiefly giant foxtail and common waterhemp, were measured from photographs at midsummer. In 2 of 3 site-yr and with the 3 site-yr average, corn yields were a nonlinear function of both in-row and between-row weed cover recovering from various PRE soil-residual herbicide treatments. In 1 of 3 site-yr, corn yields were a nonlinear function of only between-row total weed cover. Subdividing weed cover into in-row and between-row subpopulations in equations accounted for more data variability in yield estimates than including either subpopulation alone. For all 3 site-yr after PRE herbicide treatment, corn yields were a nonlinear function of only between-row visually rated total weed control. Visual evaluation was less sensitive than photographic weed cover for measuring the contribution of in-row weeds to corn yield loss and characterizing the functional form of the equations.

**Nomenclature:** Common waterhemp, *Amaranthus rudis* Sauer AMATA; giant foxtail, *Setaria faberii* Herrm. SETFA; corn, *Zea mays* L. ZEAMX 'Pioneer 33G28'.

**Key words:** Competition, interference, weed, yield.

In weed–crop interference research with untreated weeds, various empirical equations have been reported that relate crop yield to absolute or relative weed growth per unit area (Lindquist and Knezevic 2001). Absolute measures of weed growth include weed density (Murphy et al. 2002), volume (Bussler et al. 1995), shoot biomass (dry or wet weight), or leaf area index (i.e., weed total leaf area per unit ground area) (Bosnic and Swanton 1997; Knezevic et al. 1995; Kropff et al. 1992; Lindquist et al. 1998; McLachlan et al. 1993). Relative measures of weed growth, such as weed relative density and weed relative leaf cover, express weed growth as ratios, fractions, or percentages of total crop plus weed growth (i.e., weed relative leaf cover = weed leaf area [weed plus crop leaf area]<sup>-1</sup> for a unit area) (Ngouajio et al. 1999a, 1999b, 1999c).

Both absolute and relative measures of weed growth are laborious, costly, and time consuming to gather. Except for weed density, many measures also require destructive plant harvesting. In contrast, measuring projected weed ground cover from digital photographs taken vertically toward the soil surface reduces the labor, time, and cost of collecting weed growth data in the field (Donald et al. 2004a, 2004b). Because gathering projected weed cover data is nondestructive, the same weed-infested area can be repeatedly photographed over time, if desired. Projected weed cover is the ratio of the measured area of the top layer of the weed canopy per unit ground area and is expressed as a percentage. It is different from visually estimated or rated weed control, weed leaf area index (i.e., total weed leaf area per

unit ground area), or Ngouajio's weed relative leaf cover [i.e., weed leaf area (weed plus crop leaf area)<sup>-1</sup> per unit area] (Ngouajio et al. 1999a, 1999b, 1999c). Although both photographic projected weed cover and visually rated weed ground cover measure the same thing, visual estimation is based on human vision, lacks a calibration scale, and requires subjective human judgment (Donald 2006). Visually rated weed ground cover and visually rated weed control are not the same thing. Many limitations of visually rated weed control (Donald 2006) apply to visual weed cover estimation. In contrast to visual evaluation, photographic weed cover creates a permanent record, is calibrated against a scale, and is measured using an objective scientific procedure. Photographic weed cover has the characteristics of a scientific measurement at an ordinal scale, whereas visually rated weed cover or control does not.

Recently, corn yields were shown to be reduced differently by untreated mixed populations of weeds growing in and between corn rows (Donald and Johnson 2003). Weeds growing only between rows reduced corn yields as much or more than weeds growing only in rows. However, equations have not been reported before for corn yields as a function of both in-row and between-row projected total weed cover, measured from photographs.

Because soil-residual PRE herbicides can both decrease and delay susceptible annual weed emergence and reduce subsequent growth, weeds escaping or surviving herbicides reduce crop yields less than untreated weeds (Adcock and Banks 1991; Black and Dyson 1993; Weaver 1991). Weeds

may survive or recover from herbicide treatment, and weed emergence may normally occur or be delayed until after soil herbicide concentrations decrease below phytotoxic levels. Equations for many herbicide dose–response bioassays have been reported for weeds growing under controlled environmental conditions without crop interference (Streibig and Kudsk 1992). However, equations have not been reported before for corn yields vs. the cover of mixed weed populations recovering from soil-residual PRE herbicides in the field.

In much published applied research, multiple measurements of weed response (e.g., rated control) and crop response (e.g., yield) are related to the same plot treatments. However, relations among these multiple measurements are assumed, and the functional forms between these relations are almost never examined or reported. One research goal was to determine equations relating corn yields to in-row and between-row total weed cover measured from photographs of mixed weed populations that were recovering from soil-residual PRE herbicide treatment. The null hypothesis concerned the shape of the regression equations between corn yield and these independent variables, rather than whether a relation simply existed. Consequently, the null hypothesis was that corn yield was a linear function, and the alternative hypothesis was that corn yield was a nonlinear function for each of these independent variables, as expected on the basis of reported equations for weed interference from untreated weeds (Lindquist and Knezevic 2001). The goal was neither to compare yield-loss equations for herbicide-treated and untreated weeds, nor to “predict” yield loss from these variables measured early in the growing season. Another research goal was to compare equations described above with equations relating corn yields to in-row and between-row visually rated total weed control measured in the same plots of the same experiments. The null and alternative hypotheses were similar to those described above.

## Materials and Methods

### Agronomic Practices

Because published data (Donald et al. 2004b) were re-analyzed for this study, brief details are presented for field operations, treatments, measurements, and weather data. Experiments were conducted for 3 site-yr: (1) 1 yr at the University of Missouri’s Bradford Research and Extension Center in north-central Missouri near Columbia (38°53′43.5″N, 92°12′37.9″W, 269 m altitude) in 2001, and (2) 2 yr at the University of Missouri’s Greenley Memorial Research Center in northern Missouri near Novelty (40°0′45″N, 92°12′29″W, 254 m altitude) in 2001 and 2002. Corn was fertilized for a grain yield goal of 10 Mg ha<sup>-1</sup>, and ‘Pioneer 33G28’ corn seed was planted in 76-cm rows at 68,000 seed ha<sup>-1</sup>. Although mixed weed populations were present at both sites, giant foxtail was most abundant (Donald et al. 2004b). Most remaining weed cover was common waterhemp, the chief broadleaf weed present. Weeds emerged well after soil-residual PRE herbicide treatment and crop emergence (Donald et al. 2004b).

### Herbicide Treatments

Different in-row and between-row weed cover developed after different treatments with soil-residual PRE herbicides

(Donald et al. 2004b). PRE atrazine + s-metolachlor + clopyralid + flumetsulam<sup>1</sup> were applied either by broadcast application or zone application (i.e., different herbicide rates applied over and between rows) to create different percentages of between-row and in-row weed cover. Between-row and in-row zone widths were each 50% of the corn row width (76 cm). The 1× rate of atrazine + s-metolachlor + clopyralid + flumetsulam was 2.24 + 1.75 + 0.21 + 0.067 kg ai ha<sup>-1</sup>, respectively. Between-row + in-row zone herbicide rates were 0×, 0.25×, 0.5×, 0.75×, and 1× in all possible between-row + in-row zone combinations in 2001 and a subset of these treatments in 2002 (Donald et al. 2004b). Broadcast applications were made with a single-boom backpack sprayer, whereas zone herbicide applications were made with a dual boom sprayer (Donald et al. 2004b).

Treatments were arranged in a randomized complete block design with four or five blocks (Hoshmand 1994). Individual plots measured 3 by 13.7 m at the Bradford Center and 3 by 9.1 m at the Greenley Center.

### Measurements

Dates for measurements are published (Donald 2006; Donald et al. 2004b). Projected ground cover of total, grass, and broadleaf weeds (%) was measured from digital camera photographs<sup>2</sup> taken in and between crop rows (“weed cover” hereafter). Corn foliage, which was overhanging and obscuring in-row and between-row zones, was pulled back with 1-m<sup>2</sup> wooden frame panels covered with black cloth. To help mark and distinguish the in-row and between-row herbicide-treated zones in photographs, an orange-colored dowel was extended 19 cm from the crop row toward the row middle at the soil surface (Donald et al. 2004b). Four photographs per zone per plot were taken vertically (i.e., camera facing down toward the soil surface) with a digital camera at a height of 132 cm in four blocks in 2001 and five blocks in 2002. Each photograph corresponded to 1.1 m<sup>2</sup> of soil surface on the basis of photographs of a 30- by 30-cm orange calibration plate. Image analysis software was used to crop in-row and between-row zones and automatically superimpose a 20- by 20-pixel grid of lines over each cropped photograph.

In 2001, projected total weed cover (WC) was calculated using this equation:

$$WC = (nN^{-1})100 \quad [1]$$

where WC = projected weed cover of grass + broadleaf weeds (%),  $n$  = number of points where  $X$ – $Y$  grid lines both intersected and contained either grass or broadleaf weed cover categories on the basis of visual inspection, and  $N$  = total number of points where  $X$ – $Y$  grid line intersected per cropped photograph.

In 2002, the image analysis software<sup>3</sup> was used to automatically measure projected total weed cover (i.e., the software did not distinguish grass from broadleaf weed cover) (Donald et al. 2004b). In 2002, all photographs were taken under an umbrella to shade and minimize contrast between brightly lit and heavily shaded spots and ensure uniform light intensity within and between photographs. This allowed projected total weed cover to be determined using the software’s automated measurement capacity to distinguish and measure “green” weed cover from the background. In 2002, projected total weed cover was calculated as the ratio

of green pixels to total pixels per photograph, expressed as a percentage. In both years, measurements from four in-row and four between-row photographs per plot were averaged to calculate projected in-row and between-row total weed cover, respectively. The different methods that were used to measure projected total weed cover in 2001 and 2002 were linearly related to one another in a nearly 1:1.1 relationship (Donald et al. 2004b).

The same observer visually evaluated (rated) total weed control in rows and between rows in mid-summer on the basis of a scale of 0% (no control) to 100% (complete kill) for all site-years. After cutting borders at either end of all plots, corn was combine-harvested from the two center rows in an area measuring 1.5 by 10.6 m at Bradford and 1.5 by 8.2 m at Greenley, and grain yields were adjusted to 15% moisture content.

## Statistical Analysis

Data for each site-year and for the 3-yr average were separately subjected to response surface regression (Myers and Montgomery 2002; SPSS 2001). Least-square regression software<sup>4</sup> was used to fit linear and nonlinear equations (i.e., regression functions or models) relating corn yields ( $\text{kg ha}^{-1}$ ), the dependent variable ( $Z$ ), to two independent variables, in-row ( $X$ ) and between-row ( $Y$ ) total weed cover (%), which were measured from photographs. The complete default nonlinear regression equation containing linear and quadratic terms was:

$$Z = a + bX + cX^2 + dY + eY^2 \quad [2]$$

Stepwise regression analysis was used to select the most parsimonious model for each site-year and for their average (Motulsky and Christopoulos 2003). Likewise, corn yields were fitted to in-row ( $X$ ) and between-row ( $Y$ ) rated total weed control (%). In the original experiment, different herbicide application techniques and rates created different weed cover "treatments" in different blocks. In this analysis, these derived between-row and in-row total weed cover treatments were not replicated; consequently, lack-of-fit statistics were not calculated for the regression models. Software<sup>5</sup> was used to prepare three-dimensional contour graphs of the "best" regression models for corn yields ( $\text{kg ha}^{-1}$ ) using the software's default Loess smoothing feature. Smoothed contour line intervals between successive contour lines of corn yield ( $\text{kg ha}^{-1}$ ) were chosen arbitrarily and should not be interpreted as statistically different from each other.

## Results and Discussion

### Corn Yields vs. In-Row and Between-Row Total Weed Cover

One null hypothesis was that corn yield would be a function of both in-row and between-row total weed cover after soil-residual PRE herbicide treatment. The function was expected to be nonlinear, on the basis of published crop interference research with untreated weed populations (Lindquist and Knezevic 2001). For 2 of 3 site-yr (Greenley in 2001 and 2002) and for the 3 site-yr average, this null hypothesis was verified (Figure 1; Table 1). For these cases, equations that included nonlinear terms for both in-row and

between-row total weed cover accounted for more yield variability than equations lacking either of these variables. However, in 1 site-yr (Bradford 2002) corn yield was a negative nonlinear function of only between-row total weed cover (Bradford in 2001). In all cases, nonlinear equations accounted for more data variability in corn yield than linear equations. These results verify that the expected nonlinear functional form of the yield loss equations apply for PRE herbicide-treated weed competing in corn, similarly for untreated weed competing with corn (Lindquist and Knezevic 2001). Moreover, subdividing weed cover into in- and between-row subpopulations accounted for more data variability in corn yield than using either subpopulation alone in 2 of 3 yr. Equations differed among site-years (Figure 1; Table 1), as expected, because yield potential differed because of weather variation among site-years (Donald et al. 2004b).

In published weed-crop interference research conducted without soil-residual PRE herbicide treatment, season-long interference by weeds growing only between rows reduced corn yields as much or more than did weeds growing only in rows (Donald and Johnson 2003). After broadcast-applied soil-residual PRE herbicides, mid-season between-row total weed cover also exceeded in-row weed cover in corn (Donald et al. 2004a, 2004b). On the basis of published observations with untreated weeds (Donald et al. 2004a), corn yields were expected to be decreased by between-row weed growth more than in-row weed growth after PRE herbicide treatment (i.e., in yield equations, either between-row quadratic terms were expected or between-row coefficients were expected to exceed in-row coefficients). These expectations were verified for all 3 site-yr and the 3-yr average after PRE herbicide treatment (Figure 1; Table 1).

### Corn Yields vs. In-Row and Between-Row Rated Total Weed Control

Observations of rated total weed control were made by one individual who visually inspected weed growth along rows from one edge of the plots. For all 3 site-yr after PRE herbicide treatment, corn yields were a function of only between-row rated total weed control alone (Figure 1; Table 1). Thus, for measuring the contribution of in-row weeds to corn yield loss in this experiment, visually rated weed control was less sensitive than photographic weed cover. In published research (Donald 2006), observers' weed control ratings for entire plots for this experiment were biased and influenced more by weeds growing between corn rows than in corn rows.

Corn yield loss equations using rated total weed control were nonlinear in 2 of 3 site-yr (Bradford in 2001 and Greenley in 2002) and linear in 1 site-yr (Greenley in 2001). Thus, for determining the expected nonlinear form of yield loss equations (Lindquist and Knezevic 2001), visually rated total weed control was less consistent than total weed cover. For the 3 site-yr average, corn yields were a nonlinear function of both rated in-row and between-row total weed control, but rated between-row total weed control contributed more than rated in-row total weed control to yield estimates. This was likely due to raters' visual attention being drawn to the weeds growing between rows (Donald 2006).

Nonlinear equations relating corn yield to total weed con-

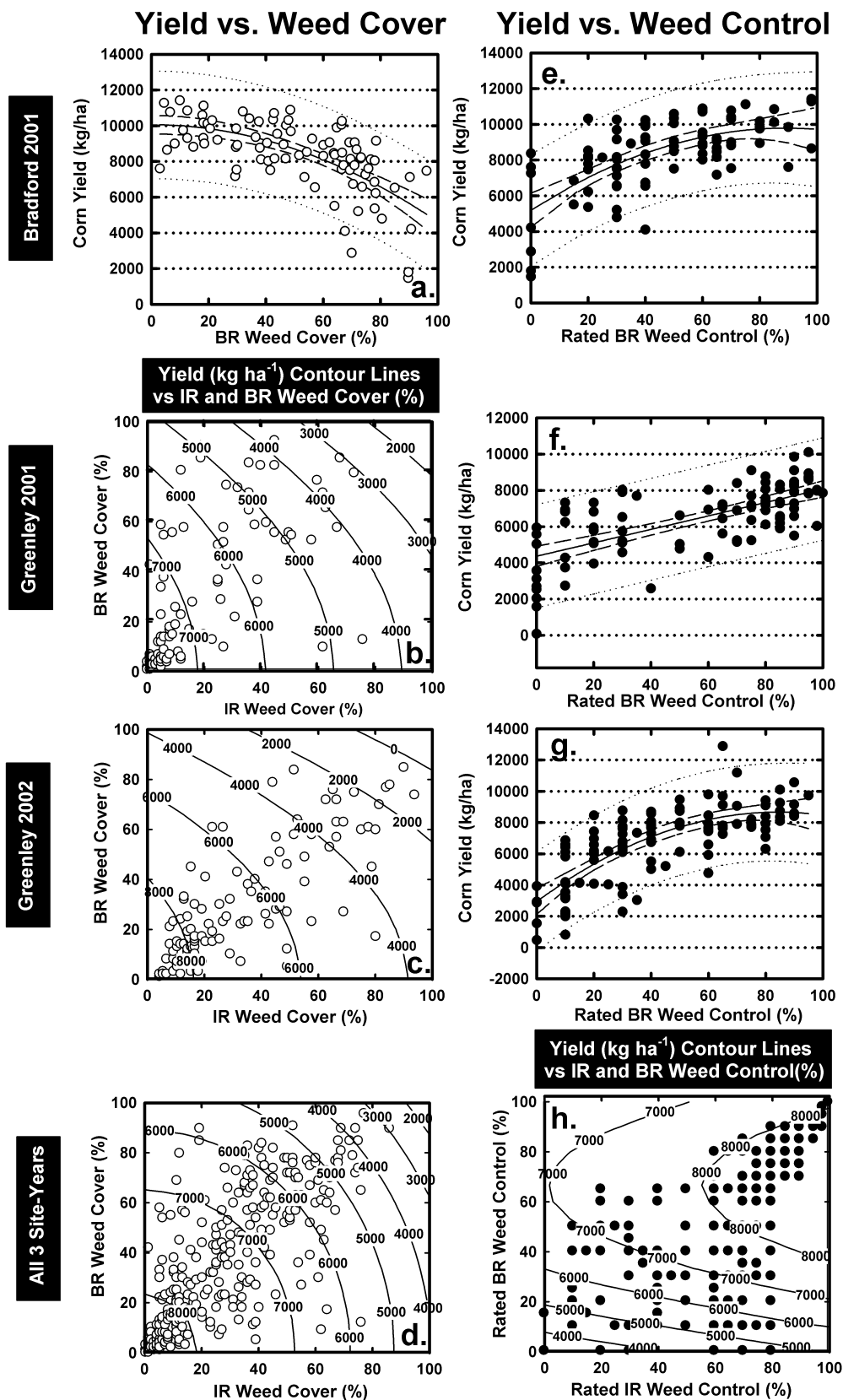


FIGURE 1. Corn yield ( $Y$ , kg ha<sup>-1</sup>) vs. between-row (BR) total weed cover ( $X$ , %) (left panels, a) or rated BR total weed control ( $X$ , %) (right panels, e to g.) at mid-season for 3 site-years and their average. Observations (open and solid circles for weed cover and control, respectively), fitted regression equations (solid lines), 95% confidence intervals (dashed lines), and 95% prediction intervals (dotted lines) are presented. In some site-yr and the 3 site-yr average, contour lines of corn yield ( $Z$ , kg ha<sup>-1</sup>) vs. either both in-row ( $X$ , IR) and between-row ( $Y$ , BR) total weed cover (%) (left panels, b through d) or both in-row ( $X$ ) and between-row ( $Y$ ) rated total weed control (%) (right panels, h). The intervals between successive contour lines of corn yield are arbitrary. In contour plots, data points representing combinations of  $X$  and  $Y$  independent variables are superimposed over the contour line graph [i.e., open circles (left panels) or solid circles (right panels)]. See Table 1 for regression equations.

TABLE 1. Regression equations relating corn yield ( $\text{kg ha}^{-1}$ ) (Figure 1), the dependent variables ( $Z$ ), to the independent variables, in-row ( $X$ ) and between-row ( $Y$ ) total weed cover (%) or in-row ( $X$ ) and between-row ( $Y$ ) rated total weed control (%) at 3 site-yr and their 3 site-yr average (Figure 1). Parameter coefficients ( $\pm$  standard errors) and adjusted  $R^2$  values corrected for degrees of freedom are presented. When the equation for estimating corn yield contains only two variables,  $Y$  is corn yield, and  $X$  is either between-row total weed cover or rated total control. When equations contain three variables,  $Z$  is corn yield, and  $X$  and  $Y$  correspond to between-row and in-row cover, respectively, or rated total weed control, respectively.

Site-year	Dependent variable (Y or Z)	Independent variable (X)	Independent variable (Y)	Equation	$R^2$
Bradford 2001	Corn yield ( $\text{kg ha}^{-1}$ )	Between-row total weed cover (%)		$Y = 10047.36 (\pm 260.53) - 0.54 (\pm 0.07)X^2$	0.44
Greenley 2001	Corn yield ( $\text{kg ha}^{-1}$ )	In-row total weed cover (%)	Between-row total weed cover (%)	$Z = 7738.45 (\pm 197.93) - 41.89 (\pm 8.67)X$ $0.25 (\pm 0.08)Y^2$	0.46
Greenley 2002	Corn yield ( $\text{kg ha}^{-1}$ )	In-row total weed cover (%)	Between-row total weed cover (%)	$Z = 8861.13 (\pm 230.73) - 53.19 (\pm 10.42)X$ $0.50 (\pm 0.11)Y^2$	0.64
All 3 site-yrs	Corn yield ( $\text{kg ha}^{-1}$ )	In-row total weed cover (%)	Between-row total weed cover (%)	$Z = 8170.20 (\pm 151.78) - 0.41 (\pm 0.10)X^2$ $0.27 (\pm 0.07)Y^2$	0.26
Bradford 2001	Corn yield ( $\text{kg ha}^{-1}$ )	Between-row rated total weed control (%)		$Y = 5184.10 (\pm 477.42) + 103.21 (\pm 21.64)X - 0.58 (\pm 0.22)X^2$	0.43
Greenley 2001	Corn yield ( $\text{kg ha}^{-1}$ )	Between-row rated total weed control (%)		$Y = 4316.44 (\pm 279.23) + 37.08 (\pm 4.19)X$	0.44
Greenley 2002	Corn yield ( $\text{kg ha}^{-1}$ )	Between-row rated total weed control (%)		$Y = 2947.16 (\pm 419.52) + 135.47 (\pm 21.68)X - 0.80 (\pm 0.22)X^2$	0.56
All 3 site-yrs	Corn yield ( $\text{kg ha}^{-1}$ )	In-row rated total weed control (%)	Between-row rated total weed control (%)	$Z = 3223.66 (\pm 315.73) + 18.06 (\pm 5.35)X$ $+ 114.53 (\pm 13.26)Y - 0.86 (\pm 0.13)Y^2$	0.43

tol on a plot basis was reported previously for this experiment (Donald 2006). This is the first report of nonlinear equations for corn yield as a function of both in-row and between-row total weed control after soil-residual PRE herbicides. Harvey and Wagner (1994) observed that field and sweet corn yields were linearly related to "weed pressure," a visual estimate of weed volume, but they did not partition weeds into in-row and between-row components. Although rated total weed control may be related to weed pressure, equations were linear and, thus, consistent with the observations of Harvey and Wagner (1994) in only 1 of 3 site-yr. Although visually rated weed control is commonly used to screen treatments to "pick a winner" treatment for recommendation to farmers, it is not commonly used to estimate yield loss. Although visually rated weed control is implicitly assumed to be related to yield loss in such research, there are few published reports documenting the functional form of these relations (Harvey and Wagner 1994).

Adjusted  $r^2$  values reflect the amount of data variation explained by the regression models (Table 1). Excluding the 3 site-yr average for corn yield equations vs. in-row and between-row total weed cover, adjusted  $r^2$  values ranged from 0.44 to 0.64. For equations using in-row and between-row rated total weed control, adjusted  $r^2$  values ranged from 0.43 to 0.56. In all 3 site-yr, either projected total weed cover, measured from photographs, or visually rated total weed control accounted for similar amounts of data variation in corn yields. However, although both variables accounted for much data variability in yield, neither independent variable accurately estimated corn yields, as expected for field measurements alone. Other factors that control maximum yield potential between years and sites, such as weather, soil characteristics, and crop management, likely accounted for the large residual error in the corn yield equations (Figure 1; Table 1).

It is now possible to quickly photograph weed cover in the field with digital cameras and to semiautomatically measure weed cover with image analysis software later (Donald et al. 2004b). Projected weed cover can be measured by individual weed species, categories of weeds (i.e., grass, broadleaf, or sedge), or total weed cover (Donald et al. 2004b). Archived photographs provide a permanent record, and the methodology minimizes error due to human vision and subjective judgment in visually rating either weed control or cover.

Weed cover and rated weed control provide different information. At Bradford and Greenley in 2001, zone herbicide treatments created a range of in-row and between-row total weed cover values that reduced corn yields (Figure 1). Even though identical herbicide treatments were applied to both sites in 2001, the resulting distribution of in-row and between-row weed cover differed between site-years. In contrast to total weed cover measured from photographs, subjectively rated total weed control does not create a permanent record of raw data and works best only at the low- and high-value extremes (Donald 2006). In addition, weed control ratings are specific to the site and year in which they are gathered because weed control rating has no absolute standard scale of comparison, other than the weedy check (i.e., 0%). Moreover, weed control ratings cannot be compared across sites or years because the weedy checks change across sites and years in undefined ways (i.e., no absolute

standard of comparison across years). Weed cover does not have these limitations and may be valuable as input data for computer modeling of weed-crop interference.

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

## Sources of Materials

<sup>1</sup> Bicep II Magnum (atrazine + s-metolachlor), Syngenta, P.O. Box 8353, Greensboro, NC 27419; and Hornet (clopyralid + flumetsulam), Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268.

<sup>2</sup> Olympus D-620 L digital camera in 2001 and Olympus C4040 zoom digital camera in 2002, Olympus America Inc., P.O. Box 9058, Melville, NY 11747.

<sup>3</sup> Sigma Scan Pro version 5 software, SPSS Science, SPSS Inc., 233 South Wacker Drive, 11th Floor, Chicago, IL 60606.

<sup>4</sup> SPSS version 12, SPSS Science, SPSS Inc., 233 South Wacker Drive, 11th Floor, Chicago, IL 60606.

<sup>5</sup> Sigma Plot 2000 software, SPSS Inc., 444 North Michigan Avenue, Chicago, IL 60611.

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## Literature Cited

- Adcock, T. E. and P. A. Banks. 1991. Effects of preemergence herbicides on competitiveness of selected weeds. *Weed Sci.* 39:54–56.
- Black, I. D. and C. B. Dyson. 1993. An economic threshold model for spraying herbicides in cereals. *Weed Res.* 33:279–290.
- Bosnic, A. C. and C. J. Swanton. 1997. Influence of barnyardgrass (*Echinochloa crus-galli*) time of emergence and density on corn (*Zea mays*). *Weed Sci.* 45:276–282.
- Bussler, B. H., B. D. Maxwell, and K. J. Puettmann. 1995. Using plant volume to quantify interference in corn (*Zea mays*) neighborhoods. *Weed Sci.* 43:586–594.
- Donald, W. W. 2006. Between observer differences limit rated weed control. *Weed Technol.* In press.
- Donald, W. W., D. Archer, W. G. Johnson, and K. Nelson. 2004b. Zone herbicide application controls annual weeds and reduces residual herbicide use in corn. *Weed Sci.* 52:821–833.
- Donald, W. W. and W. G. Johnson. 2003. Interference effects of weed-infested bands in or between crop rows on field corn (*Zea mays*) yield. *Weed Technol.* 17:755–763.
- Donald, W. W., W. G. Johnson, and K. A. Nelson. 2004a. In-row and between-row interference by corn (*Zea mays*) modifies annual weed control by preemergence residual herbicide. *Weed Technol.* 18:487–504.
- Harvey, R. G. and C. R. Wagner. 1994. Using estimates of weed pressure to establish crop yield loss equations. *Weed Technol.* 8:114–118.
- Hoshmand, A. R. 1994. *Experimental Research Design and Analysis. A Practical Approach for Agricultural and Natural Sciences.* Boca Raton, FL: CRC Press. Pp. 59–170.
- Knezevic, S. Z., S. F. Weise, and C. J. Swanton. 1995. Comparison of empirical models depicting density of *Amaranthus retroflexus* L. and relative leaf area as predictors of yield loss in maize (*Zea mays* L.). *Weed Res.* 35:207–214.
- Kropff, M. J., S. E. Weaver, and M. A. Smits. 1992. Use of ecophysiological models for crop-weed interference: relations amongst weed density, relative time of weed emergence, relative leaf area, and yield loss. *Weed Sci.* 40:296–301.
- Lindquist, J. L. and S. Z. Knezevic. 2001. Quantifying crop yield response to weed populations: applications and limitations. Pages 205–232 in

- R.K.D. Peterson and L. G. Higley, eds. Biotic Stress and Yield Loss. Boca Raton, FL: CRC Press.
- Lindquist, J. L., D. A. Mortensen, and B. E. Johnson. 1998. Mechanisms of corn tolerance and velvetleaf suppressive ability. *Agron. J.* 90:787–792.
- McLachlan, S. M., M. Tollenaar, C. J. Swanton, and S. F. Weiss. 1993. Effect of corn-induced shading on dry matter accumulation, distribution, and architecture of redroot pigweed (*Amaranthus retroflexus*). *Weed Sci.* 41:568–573.
- Motulsky, H. and A. Christopoulos. 2003. GraphPad PRISM Version 4.0. Fitting Models to Biological Data Using Linear and Nonlinear Regression. A Practical Guide to Curve Fitting. San Diego, CA: GraphPad Software. Pp. 143–159.
- Murphy, C., D. Lemerle, R. Jones, and S. Harden. 2002. Use of density to predict crop yield loss between variable seasons. *Weed Res.* 42:377–384.
- Myers, R. H. and D. C. Montgomery. 2002. Response Surface Methodology. Process and Product Optimization Using Designed Experiments. 2nd ed. New York: John Wiley & Sons. Pp. 17–154.
- Ngouajio, M., C. Lemieux, and G. D. Leroux. 1999a. Prediction of corn (*Zea mays*) yield loss from early observations of the relative leaf area and the relative leaf cover of weeds. *Weed Sci.* 47:297–304.
- Ngouajio, M., G. D. Leroux, and C. Lemieux. 1999b. Influence of images recording height and crop growth stage on leaf cover estimates and their performance in yield prediction models. *Crop Prot.* 18:501–508.
- Ngouajio, M., G. D. Leroux, and C. Lemieux. 1999c. A flexible sigmoidal model relating crop yield to weed relative leaf cover and its comparison with nested models. *Weed Res.* 39:329–343.
- SPSS. 2001. SPSS User's Guide. Volume 11. Chicago: SPSS.
- Streibig, J. C. and P. Kudsk. 1992. Herbicide Bioassays. Boca Raton, FL: CRC Press. 270 p.
- Weaver, S. E. 1991. Size-dependent economic thresholds for three broadleaf weed species in soybeans. *Weed Technol.* 5:674–679.

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